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A Wideband Low-Profile Efficiency-Improved Transmitarray Antenna With Over-1-bit Phase-Shifting Elements

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ABSTRACT This paper describes a wideband, low-profile and efficiency-improved transmitarray antenna achieved by employing over-1-bit phase-shifting elements and incorporating optimized phase compensation scheme. Firstly, a wideband ultrathin 1-bit phase-shifting unit cell is presented based on the polarization twisting feature of the twisted stacking aperture structure. A minor variation in unit-cell geometry is then introduced to add more degrees of freedom in phase adjustment while maintaining nearly same low insertion loss within a wide frequency range. Moreover, the resultant performances of transmitarrays using different phase compensation schemes are compared. An optimized scheme that has a minimized average phase error and effectively enhances the aperture efficiency is adopted. Results of a 21.5% 1-dB gain bandwidth, 0.127-\(\lambda_0\) aperture thickness and 40% aperture efficiency are observed from the fabricated 14 \(\times\) 14 transmitarray antenna.

INDEX TERMS Flat lens antenna, low profile, thin aperture, transmitarray antenna, wide gain bandwidth.

I. INTRODUCTION
Transmitarray antenna, also known as flat lens, uses a planar phase shifting surface to transform the spherical incident wave from the feed into a predescribed outgoing wave [1]–[11]. It shows a number of advantages, such as light weight, low cost and simple feeding mechanism over conventional high-gain antennas. In addition, transmitarray avoids the feed blockage issue and could attain better conformality as compared to its reflectarray counterpart [12]–[16]. Such feasible characteristics have made transmitarray an emerging candidate for modern high-gain antenna design.

Despite its attractive features, one critical issue associated with transmitarray is the inherent narrow bandwidth. A number of different designs based on the two most popular approaches, i.e., the multilayer-frequency selective surface (M-FSS) approach [4], [5], [17]–[20] and the receive/transmit approach [6], [7], [9], have been carried out to extend the bandwidth of transmitarray. In the M-FSS type method, wideband performance is realized by stacking multiple (usually larger than three) FSS layers. The transmitarray profile could be relatively high as the thickness of each layer is usually more than 0.1 \(\lambda_0\) [17], [18]. As for the receive/transmit approach, unit-cell thickness could be potentially smaller since only the receive and transmit layers are mandatory. Bandwidth enhancement is achieved mainly through designing a wideband receive/transmit structure. One of the latest wideband design in this category reports a 3-dB gain bandwidth of 24% with a thickness of 0.28 \(\lambda_0\) [6]. There are also other techniques developed to address the bandwidth limitation of transmitarray. In [4], 16% 1-dB gain bandwidth and 0.25-\(\lambda_0\) aperture thickness is achieved using wideband band-pass filter. More recently, a 0.42-\(\lambda_0\) thick transmitarray featuring a wide bandwidth has been proposed based on the tightly coupled dipole elements [21].

In this paper, we present a wideband low-profile transmitarray design based on the stacking aperture structure [22] and the polarization twisting capability of twisted
The configuration of the basic transmitarray element is depicted in Fig. 1. The presented unit cell, as shown, is a twisted stacking aperture structure containing three stacked and twisted slotted-ring apertures. Three metal layers separated by two identical substrates (with a thickness of 1.575 mm and a relative permittivity of 2.2) are adopted to accommodate the apertures. On each metal layer, a slotted-ring aperture is etched. The slotted-ring apertures on the top and bottom layers are arranged to be orthogonal and the one on the middle layer is oriented towards the diagonal direction. Stated in another way, the slotted-ring apertures on the middle and bottom layers are rotated by 45° and 90°, respectively, with respect to the one on top. A 0.038-mm-thick bonding film (relative permittivity of 2.28) is placed beneath the middle metal layer to facilitate fabrication. Periodicity of the unit cell is set as 10 mm, corresponding to 0.4 \( \lambda_0 \) at the central frequency of 12 GHz. Inner and outer radii of the ring as well as other geometric specifications of the unit cell are listed in Table 1.

The transmission coefficients of the proposed basic unit cell when illuminated by \( x \)- and \( y \)-polarized incident waves are plotted in Fig. 2(a) and Fig. 2(b), respectively. As can be seen from Fig. 2(a), an \( x \)-polarized wave can pass through the structure efficiently with a majority of its energy transferred into a \( y \)-polarized outgoing wave. The 1-dB insertion loss bandwidth of the unit cell reaches 25\%, covering 10.5 GHz to 13.5 GHz. The transmission coefficient almost remains identical for different wave incident angles. The cross-polarization (the \( x \)-polarization) level in the transmitted wave is below −15 dB at most frequencies of interest. It is also learnt, from Fig. 2(b), that the proposed structure does not allow the \( y \)-polarized incident wave to be transmitted. Therefore, the structure is suitable to be used as a low-insertion-loss transmitarray element with polarization twisting feature.

The wideband operation mechanism of the twisted stacking apertures has been explained in previous studies [22], [23]. Owning to the strong inter-layer coupling [22] and the excitation of guided resonance modes [23], broadband transmission and polarization rotating functionalities are achieved in such a low-profile form. It has also been revealed that the twist angle of polarization of the transmitted wave with respect to that of the incident wave is controlled by the relative rotation (90° in this design) between the two slotted-ring apertures at the top and bottom layers.

By further investigating the polarization twisting feature, it is found in this paper that by fixing the rotation angle between top and bottom slotted-ring apertures as 90° and symmetrically altering the orientation of the middle aperture (from 45° to \(-45°\) direction), the transmitted wave will stay in the same polarization that is orthogonal to the incident wave but exhibit an inversed phase, as shown by the electric-field distributions in Fig. 3. It can be identified that the electromagnetic fields gradually change their polarization when coupling through the three layers and the middle slotted-ring aperture acts as a director to guide the wave during polarization rotation. Altering the orientation of the middle aperture (from 45° to \(-45°\) direction) will change the direction of rotation of the electromagnetic fields when they pass through. Thus, same polarization, same transmission magnitude and exactly 180° difference in transmission phase are to be expected in the two resultant outgoing waves. As plotted in Fig. 4, a stable transmission phase difference of 180° is observed over the 1-dB operating band for the two middle aperture orientations. Thus, one is able to adjust the transmission phase with 1-bit resolution by manipulating only the orientation of middle slotted-ring aperture.

### II. PROPOSED OVER-1-bit PHASE-SHIFTING ELEMENT

#### A. BASIC ELEMENT WITH 1-bit PHASE RESOLUTION

The configuration of the basic transmitarray element is depicted in Fig. 1. The presented unit cell, as shown, is a twisted stacking aperture structure containing three stacked and twisted slotted-ring apertures. Three metal layers separated by two identical substrates (with a thickness of 1.575 mm and a relative permittivity of 2.2) are adopted to accommodate the apertures. On each metal layer, a slotted-ring aperture is etched. The slotted-ring apertures on the top and bottom layers are arranged to be orthogonal and the one on the middle layer is oriented towards the diagonal direction. Stated in another way, the slotted-ring apertures on the middle and bottom layers are rotated by 45° and 90°, respectively, with respect to the one on top. A 0.038-mm-thick bonding film (relative permittivity of 2.28) is placed beneath the middle metal layer to facilitate fabrication. Periodicity of the unit cell is set as 10 mm, corresponding to 0.4 \( \lambda_0 \) at the central frequency of 12 GHz. Inner and outer radii of the ring as well as other geometric specifications of the unit cell are listed in Table 1.

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### TABLE 1. Specifications of the proposed basic unit cell.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( h_s )</th>
<th>( R_s )</th>
<th>( R_i )</th>
<th>( G )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1.575 mm</td>
<td>4.6 mm</td>
<td>3.8 mm</td>
<td>0.4 mm</td>
<td>±45 deg</td>
</tr>
</tbody>
</table>
FIGURE 2. Transmission coefficients of the unit cell when illuminated by different incident wave and different wave incident angle (θ): (a) x-polarized incident wave and (b) y-polarized incident wave.

FIGURE 3. Electric-field distributions on the slotted-ring apertures of each layer at 11 GHz: (a) rotation angle α = 45° and (b) rotation angle α = -45°.

B. OVER-1-bit DESIGN BY COMBINING GEOMETRICAL VARIATION

Discrete phase adjustment leads to a compromised directivity for the designed transmitarray since not all the required phase compensations can be readily provided [7], [8]. The effect of the number of phase shifting bits on the directivity degradation of such space-fed arrays has been studied in [24]: 1-bit phase adjustment leads to an averaged directivity drop of 3.8 dB, resulting in a comparatively low aperture efficiency.

In this design, a technique that increases the transmission phase variation by combining polarization twisting and geometrical variation is proposed to address the inherent aperture efficiency issue of the 1-bit element. The antenna directivity can be enhanced by almost 2 dB with nearly no degradation in gain bandwidth of the transmitarray (shown by the array simulation results in the next Section). The idea is to broaden the phase shifting range and, at the same time, try to preserve the low insertion loss and wideband transmission properties. As mentioned above, the low-loss and wideband transmission is mainly an aftereffect of the strong inter-layer coupling. Thus, a minor geometrical variation in the middle split-ring aperture aiming at not breaking much of the original symmetry or changing the aperture size is introduced. The geometrical variation in the middle aperture is achieved by splitting the single gap into two, and gradually enlarging the angle (β) between them, as sketched in Fig. 5(a). Coupling coefficients between neighboring layers can be slightly altered by tuning the angle (β). Two typical middle split-ring aperture configurations corresponding to α = 45°, β = 15° and α = -45°, β = 30° are depicted in Figs. 5(b) and 5(c), respectively. Benefited from the proposed two-gap modification, more degrees of freedom in

FIGURE 4. Relative phase of the co-polarization component in transmitted wave.

FIGURE 5. Configuration of the middle aperture: (a) demonstrating the element geometry evolution, (b) when α = 45°, β = 15° and (c) when α = -45°, β = 30°.
transmission phase manipulation are obtained. As can be found in Fig. 6, phase variation is now capable of covering the ranges of \([0^\circ, 26^\circ]\) and \([-180^\circ, -154^\circ]\). It is worthy mentioning that the upper limit of the variable \(\beta\) is manually set to 30° to guarantee the 1-dB insertion loss bandwidth for the element (see Fig. 7) and hence, a nearly undegraded gain bandwidth for the transmitarray.

### III. OPTIMIZATION OF PHASE COMPENSATION SCHEME

Different selection of reference phase in the compensation scheme could result in different performance for a transmitarray designed using elements with limited phase variation range. A properly selected reference phase can reduce the phase errors across the radiating aperture and therefore achieve better aperture efficiency. Optimization in phase compensation scheme is conducted for this purpose. A cost function that describes the average weighted phase error is defined.

\[
CF = \sum \sum \frac{\cos^q \theta_e(i,j)}{\max(\cos^q \theta_e(i,j), d(i,j))} \cdot \Delta \Phi_{qnt}(i,j)
\]

where \(\Delta \Phi_{qnt}(i,j)\) is the absolute phase error at each transmitarray element due to the limited phase adjustment. Amplitude pattern of the feed is represented using the \(\cos^q\) function. \(\theta_e(i,j)\) stands for the angle of each element in feed coordinates and \(d(i,j)\) is the distance between the element and the phase center of the feed. As can be seen, the defined weight of the phase errors is related to the magnitude of electromagnetic filed received on each element from the feed, making the precise phase compensation for elements in the center of the array of more importance. To intuitively illustrate the difference between different phase compensation schemes, the distributions of phase compensations and the resultant weighted phase errors across the aperture are plotted in Fig. 8. As is evident from Fig. 8, different phase compensation scheme will certainly give rise to different phase errors as long as the element phase shifting range is less than 360°.

Phase errors can be considerably reduced by picking up an optimized scheme. What is also observed is that the proposed over-1-bit element that provides more phase adjustments effectively reduces the phase error level compared to the basic element.

The simulated gains of transmitarrays designed with different phase compensation schemes and different elements are shown in Fig. 9. It is noted that both the use of over-1-bit
IV. TRANSMITARRAY PERFORMANCES

A 14 × 14 transmitarray antenna using the proposed over-1-bit element and adopting the optimized phase compensation scheme is designed, fabricated and tested. A stub-loaded horn antenna [10] is utilized as the feed. The gain of the feed horn at the frequencies of interest is around 12 dBi and a matching factor of $g = 3.5$ is assigned for feed power pattern approximation using the $\cos^2(\theta)$ model. The horn is positioned normally facing the transmitarray center. The focal-to-diameter ratio ($f/D$) is set as 0.5, providing −10 dB edge illumination.

The fabricated prototype, as shown in Fig. 10, is tested in the SATIMO Starlab near-field measurement system. Stable gain over a wide frequency range is observed. The measured realized gain, depicted in Fig. 10, matches reasonably well with the simulation results. A peak gain of 21.9 dBi, corresponding to an aperture efficiency of 40% is observed. The measured 1-dB gain bandwidth is about 21.5%, covering from 10.8 GHz to 13.4 GHz.

Radiation patterns at the two principle planes are measured and they are plotted and compared with the simulated patterns in Fig. 11. The main lobe and the occurrence of the first sidelobe are well predicted. The measured cross-polarization level is a little bit higher than that from simulation, but is still lower than −17 dB. The measured sidelobe levels are −17 dB and −21 dB in the H- and E-planes, respectively.

V. CONCLUSION

A wideband ultrathin transmitarray design based on the over-1-bit element has been proposed. Wideband over-1-bit phase adjustment is achieved based on the geometrical variation in twisted stacking apertures. The geometrical variation as well as the optimization in phase compensation scheme effectively improves the aperture efficiency of this design to a level that is comparable with other mainstream designs.
The proposed transmitarray features a 21.5% 1-dB gain bandwidth, 0.127-λ aperture thickness, and 40% aperture efficiency, making it promising for application in wideband high-gain communication systems.

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REFERENCES

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